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Super-acceleration on the Brane by Energy Flow from the Bulk

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Abstract

We consider a brane cosmological model with energy exchange between brane and bulk. Parameterizing the energy exchange term by the scale factor and Hubble parameter, we are able to exactly solve the modified Friedmann equation on the brane. In this model, the equation of state for the effective dark energy has a transition behavior changing from $w_{de}^{eff} > -1$ to $w_{de}^{eff} < -1$, while the equation of state for the dark energy on the brane has $w > -1$. Fitting data from type Ia supernova, Sloan Digital Sky Survey and Wilkinson Microwave Anisotropy Probe, our universe is predicted now in the state of super-acceleration with $w_{de0}^{eff} = -1.21$.

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A variety of cosmological observations consistently provide a compelling evidence that our universe is experiencing an accelerated expansion. A component that causes the expansion of the universe to accelerate is referred as dark energy. The traditional cosmological constant is a possible candidate of the dark energy, although the 120 orders of magnitude difference between its theoretical and observational values presents the biggest problem to theorists [1]. Another popular candidate is an exotic field with evolving equation of state [2]. However compared to the comfortable vacuum energy interpretation of the cosmological constant, the natural reason behind these exotic fields is lacking. There are also alternative models of gravity that seek to explain the accelerated expansion[3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. One interesting theory is the so-called $1/R$ gravity suggested in [3, 9], which is possible to account for the late time acceleration. While unfortunately this theory was argued suffering a conflict with gravitational tests in the solar system [13]. Recently an alternative way to avoid this conflict was proposed [14]. Another dramatic strategy to modify gravity is to imagine that we live on a brane embedded in a higher dimensional spacetime [5, 10, 12, 15], which can naturally lead to late time acceleration. In these studies, it was assumed that dark energy does not interact with matter or radiation.

Given the unknown nature of both dark energy and dark matter, which are two major contents of the universe, one might argue that an entirely independent behavior of dark energy is very special [16, 17]. A lot of investigations assuming interaction between dark energy and dark matter have been carried out [18, 19]. With the interaction between dark sectors, the standard conservation equations of matter and dark energy are violated respectively. While the Friedmann equations can be easily modified to model exchanges between different energy components, studies on dark energy models with interaction with matter fields have disclosed that the equation of state of the dark energy has a transition behavior, changing from $w_D > -1$ to $w_D < -1$ at recent stage [18, 19]. This theoretical result is consistent with the recent extensive analysis of observation data [20]. The energy exchanges between dark sectors will drive the universe to super-acceleration [18, 19, 21] and in addition it will influence the perturbation dynamics and could also be observable through the lowest multipoles of Cosmic Microwave Background (CMB) spectrum [17]. Besides the energy exchange between dark sectors considered in four-dimensional theories, the role of the energy exchange between the bulk and brane has also been investigated. The cosmic evolution of the brane in the presence of energy flow into or from the bulk has been analyzed in different setups [22, 23].

The dark energy with equation of state $w < -1$ is referred as phantom dark energy [24]. An easy way to realize the phantom dark energy is a scalar field with a wrong sign kinetic term.

However, such a model might suffer from the instability [25]. A more challenging issue is that the time dependent dark energy gives a better fitting than a cosmological constant, and in particular, the equation of state crosses -1 at redshift $z \approx 0.2$ from the above to below [26]. While it turns out it is not trivial to build dark energy model with equation of state crossing $w = -1$ [27], a component with $w < -1$ in the universe will violate all energy conditions and threaten the basis of modern physics. Therefore it is urgent and is of great interest to construct dark energy model with observed feature in the framework of modern physics. That is, one may hope that crossing -1 for the equation of state and phantom behavior of dark energy are effective (or equivalent) features, not caused by an unstable and causality-violated phantom field. Indeed, it can be done in the scalar-tensor theory [11], brane world scenario [28], and models with interactions between dark matter and dark energy, and so on.

In this paper, we will consider a brane world scenario (RSII model) [15], in which to realize the transition of w from above -1 to below -1 by introducing an energy exchange between the brane and the bulk. By approximately parameterizing the energy exchange, we are able to exactly solve the resulting Friedmann equation on the brane. The "phantom" behavior of the dark energy on the brane is caused by energy flow from the bulk. Both dark energies on the brane and from the bulk obey the causality condition. In this sense the transition of the effective dark energy equation of state could serve as a signature of the bulk-brane energy exchange.

The gravitational brane-bulk action we are going to consider is of the form

$$S = \int d^5x\sqrt{-G}\left(\frac{R_5}{2\kappa_5^2} - \Lambda_5 + \mathcal{L}_B^m\right) + \int d^4x\sqrt{-g}\,(-\sigma + \mathcal{L}_b^m)\,, \tag{1}$$

where R_5 is the curvature scalar of the five-dimensional metric, Λ_5 is the bulk cosmological constant and σ is the brane tension, $\mathcal{L}_B^m$ and $\mathcal{L}_b^m$ are the matter Lagrangian in the bulk and on the brane respectively. We are interested in the cosmological solutions with a metric

$$ds^2 = -n^2(t,y)\,dt^2 + a^2(t,y)\,\gamma_{ij}\,dx^i dy^j + b^2(t,y)\,dy^2. \tag{2}$$

The non-zero components of Einstein tensor can be written as [29]

$$G_{00} = 3\left[\frac{\dot a}{a}\left(\frac{\dot a}{a}+\frac{\dot b}{b}\right) - \frac{n^2}{b^2}\left(\frac{a''}{a}+\frac{a'}{a}\left(\frac{a'}{a}-\frac{b'}{b}\right)\right) + k\frac{n^2}{b^2}\right], \tag{3}$$

$$\begin{aligned} G_{ij} &= \frac{a^2}{b^2}\gamma_{ij}\left[\frac{a'}{a}\left(\frac{a'}{a}+2\frac{n'}{n}\right) - \frac{b'}{b}\left(\frac{n'}{n}+2\frac{a'}{a}\right) + 2\frac{a''}{a} + \frac{n''}{n}\right] \\ &\quad + \frac{a^2}{n^2}\gamma_{ij}\left[\frac{\dot a}{a}\left(-\frac{\dot a}{a}+2\frac{\dot n}{n}\right) - 2\frac{\ddot a}{a} + \frac{\dot b}{b}\left(-2\frac{\dot a}{a}+\frac{\dot n}{n}\right) - \frac{\ddot b}{b}\right] - k\gamma_{ij}, \end{aligned} \tag{4}$$

$$G_{05} = 3\left(\frac{n'}{n}\frac{\dot a}{a} + \frac{a'}{a}\frac{\dot b}{b} - \frac{\dot a'}{a}\right), \tag{5}$$

$$G_{55} = 3\left[\frac{a'}{a}\left(\frac{a'}{a}+\frac{n'}{n}\right) - \frac{b^2}{n^2}\left(\frac{\dot a}{a}\left(\frac{\dot a}{a}-\frac{\dot n}{n}\right)+\frac{\ddot a}{a}\right) - k\frac{b^2}{a^2}\right], \tag{6}$$

where γ_{ij} is the metric for the maximally symmetric three-dimensional space and $k = -1, 0, 1$ representing its curvature. In the above equations, primes and dots stand for derivatives with respect to y and t respectively. The three dimensional brane is assumed at $y = 0$. The Einstein equations are $G_{\mu\nu} = \kappa_5^2 T_{\mu\nu}$, where the stress-energy momentum tensor has bulk and brane components and can be written as

$$T^{\mu}{}_{\nu} = T^{\mu}{}_{\nu}|_{\sigma,\,b} + T^{\mu}{}_{\nu}|_{m,b} + T^{\mu}{}_{\nu}|_{\Lambda,\,B} + T^{\mu}{}_{\nu}|_{m,B}, \tag{7}$$

where

$$\begin{aligned} T^{\mu}{}_{\nu}|_{\sigma,\,b} &= \frac{\delta(y)}{b}\,\mathrm{diag}(-\sigma,\,-\sigma,\,-\sigma,\,-\sigma,\,0), &(8)\\ T^{\mu}{}_{\nu}|_{\Lambda,\,B} &= \mathrm{diag}(-\Lambda_5,\,-\Lambda_5,\,-\Lambda_5,\,-\Lambda_5,\,-\Lambda_5), &(9)\\ T^{\mu}{}_{\nu}|_{m,\,b} &= \frac{\delta(y)}{b}\,\mathrm{diag}(-\rho,\,p,\,p,\,p,\,0), &(10) \end{aligned}$$

ρ and p are energy density and pressure on the brane, respectively.

Assuming the Z_2 symmetry around the brane, we can obtain

$$\begin{aligned} a'_{+} &= -\,a'_{-} = -\frac{\kappa_5^2}{6}\,a_0\,b_0\,(\sigma+\rho), &(11)\\ n'_{+} &= -\,n'_{-} = \frac{\kappa_5^2}{6}\,b_0\,n_0\,(-\sigma+2\rho+3p), &(12) \end{aligned}$$

by integrating Eqs. (3) and (4) with respect to y around $y = 0$, where the subscripts "+" and "−" stand for $y > 0$ and $y < 0$ respectively, which represent two sides of the brane. In addition, as usual, the subscript "0" denotes quantities are evaluated at $y = 0$.

From (5) and (6), we obtain

$$\begin{aligned} \frac{n'_0\,\dot a_0}{n_0\,a_0} + \frac{a'_0\,\dot b_0}{a_0\,b_0} - \frac{\dot a'_0}{a_0} &= \frac{\kappa_5^2}{3}\,T_{05}, &(13)\\ 3\left\{\frac{a'_0}{a_0}\left(\frac{a'_0}{a_0}+\frac{n'_0}{n_0}\right) - \frac{b_0^2}{n_0^2}\left[\frac{\dot a_0}{a_0}\left(\frac{\dot a_0}{a_0}-\frac{\dot n_0}{n_0}\right)+\frac{\ddot a_0}{a_0}\right] - k\frac{b_0^2}{a_0^2}\right\} &= -\kappa_5^2\,\Lambda_5\,b_0^2 + \kappa_5^2\,T_{55}, &(14) \end{aligned}$$

where T_{05} and T_{55} are the 05 and 55 components of $T_{\mu\nu}|_{m,\,B}$ evaluated on the brane. Employing Eqs. (11) and (12), we can derive

$$\begin{aligned}
\dot{\rho}+3\frac{\dot{a}_0}{a_0}(\rho+p) &= -\frac{2n_0^2}{b_0}T^0_{\ 5}, & (15)\\
\frac{1}{n_0^2}\left[\frac{\ddot{a}_0}{a_0}+\left(\frac{\dot{a}_0}{a_0}\right)^2-\frac{\dot{a}_0\,\dot{n}_0}{a_0\,n_0}\right]+\frac{k}{a_0^2} &= \frac{\kappa_5^2}{3}\left(\Lambda_5+\frac{\kappa_5^2\,\sigma^2}{6}\right)\\
&\quad -\frac{\kappa_5^4}{36}\left[\sigma(3p-\rho)+\rho(3p+\rho)\right]-\frac{\kappa_5^2}{3}T^5_{\ 5}. & (16)
\end{aligned}$$

Taking an appropriate gauge with the coordinate frame $b_0=n_0=1$, Eqs. (15) and (16) can be reexpressed as

$$\begin{aligned}
\dot{\rho}+3H(1+w)\rho &= -2\,T^0_{\ 5}, & (17)\\
\left(\frac{\dot{a}}{a}\right)^2 &= \lambda-\frac{\kappa}{a^2}+\beta\,\rho^2+2\,\gamma\,(\rho+\chi), & (18)\\
\dot{\chi}+4H\chi &= 2\left(\frac{\rho}{\sigma}+1\right)T^0_{\ 5}-\frac{12}{\kappa_5^2}\frac{H}{\sigma}T^5_{\ 5}, & (19)
\end{aligned}$$

where $\beta=\frac{\kappa_5^4}{36}$ and $\gamma=\frac{\sigma\,\kappa_5^4}{36}$. $\lambda\frac{\kappa_5^2}{6}\left(\Lambda_5+\frac{\kappa_5^2\,\sigma^2}{6}\right)$ is the effective cosmological constant on the brane.

In order to derive a solution that is largely independent of the bulk dynamics, we can neglect $T^5_{\ 5}$ term by assuming that the bulk matter relative to the bulk vacuum energy is much less than the ratio of the brane matter to the brane vacuum energy [22]. Considering this approximation and concentrating on the low-energy region with $\rho/\sigma \ll 1$, Eqs. (17)-(19) can be simplified into

$$\begin{aligned}
\dot{\rho}+3H(1+w)\rho &= -2\,T^0_{\ 5}=T & (20)\\
H^2 &= \frac{8\pi G_4}{3}(\rho+\chi)-\frac{k}{a^2}+\lambda & (21)\\
\dot{\chi}+4H\chi &\approx 2\,T^0_{\ 5}=-T. & (22)
\end{aligned}$$

Thus with the energy exchange T between the bulk and brane, the usual energy conservation is broken down. In the following we will consider that there are two dark components in the universe, dark matter and dark energy, $\rho=\rho_m+\rho_{de}$. The bulk-brane energy exchange will break the adiabatic equation either for the dark matter or the dark energy. We will study these two cases respectively. In our discussion, we will take $\lambda=0$ and $k=0$.

For the first case, we assume that the adiabatic equation for the dark matter is satisfied while it is violated for the dark energy due to the energy exchange between the brane and the bulk,

$$\begin{aligned}
\dot{\rho}_m+3H\rho_m &= 0, & (23)\\
\dot{\rho}_{de}+3H(1+w)\rho_{de} &= T. & (24)
\end{aligned}$$

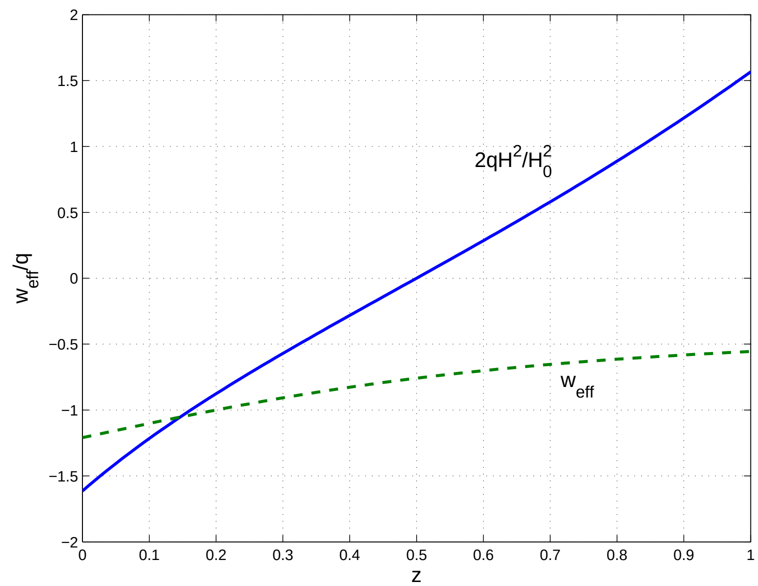

Figure 1: Evolution of the deceleration parameter and the equation of state for the effective dark energy.

Thus the evolution of dark sectors have the form $\rho_m = \rho_{m0}/a^3$, and $\rho_{de} = \exp\left[-\int 3H(1+w)dt\right]\left\{\int T \exp\left[\int 3H(1+w)dt\right] dt + C\right\}$. Assuming w being a constant and taking the ansatz $T = T_0 H a^n$ with T_0 and a two constants, we get $\rho_{de}\frac{C}{a^{3(1+w)}} + \frac{T_0\, a^n}{n+3(1+w)}$. Some remarks here are in order. To get a cosmological model based on Eqs. (20)-(22), one has to know the energy exchange T. Unfortunately, it is not yet available and obviously it depends on mechanism which produces the energy exchange. Some references in [22] take the ansatz $T \sim \rho^n$. In that case, Eqs. (20) and (22) cannot be integrated analytically and a numerical approach has to be adopted. Some papers in [22] consider the case without dark energy on the brane and the late-time acceleration is caused by the effective cosmological constant, dark radiation and the energy exchange with the ansatz $T \sim \rho^n$. Umezu *et al.* in [22] considered the case with $T \sim a^{-n}H^3$. The authors of [23] generalized these discussions to the case with an induced gravity term on the brane and with the ansatz $T \sim \rho^n$. Clearly in those cases, a late-time stable attractor with accelerated expansion exists. In our setup, both the dark matter and dark energy with $w > -1$ appear on the brane. The ansatz $T \sim Ha^n$ is taken so that one can directly integrate (20) and (22) and obtain their analytic expressions. In addition, we will consider two cases: one is to transfer the bulk energy T to the dark energy on the brane; the other is to dark matter on the brane. These two cases have significant differences on the cosmic observations.

Now we substitute our ansatz of the bulk-brane energy flow into Eq. (22), and have

$$\chi = \frac{C_1}{a^4} - \frac{T_0}{4+n} a^n, \tag{25}$$

where C_1 is an integration constant. Inserting it into Eq. (21), the Friedmann equation reads

$$H^2 = \frac{8\pi G_4}{3}\left[\frac{\rho_{m0}}{a^3} + \frac{C}{a^{3(1+w)}} + \frac{T_0\,(1-3w)a^n}{(4+n)[n+3(1+w)]}\right], \tag{26}$$

where we have neglected the dark radiation term $\sim a^{-4}$, namely $C_1 = 0$, since we have more interest in the late time era of the universe.

Another possibility is to consider transferring the bulk-brane energy exchange to the dark matter on the brane, and keeping the standard conservation equation for the dark energy on the brane,

$$\dot{\rho}_m + 3H\rho_m = T, \tag{27}$$

$$\dot{\rho}_{de} + 3H(1+w)\rho_{de} = 0. \tag{28}$$

By assuming w as a constant, and using the ansatz for T, the evolution of dark sectors become $\rho_{de} = \frac{\rho_{de0}}{a^{3(1+w)}}$ and $\rho_m = \frac{D}{a^3} + \frac{T_0}{3+n}\, a^n$. From Eq. (22), the generalized dark radiation density can be obtained as $\chi = \frac{D_1}{a^4} - \frac{T_0}{4+n}\, a^n$. Thus the Friedmann equation has the form

$$H^2 = \frac{8\pi G_4}{3}\left(\frac{D}{a^3} + \frac{\rho_{de0}}{a^{3(1+w)}} + \frac{T_0\, a^n}{(3+n)(4+n)}\right), \tag{29}$$

where a term related to the dark radiation has also been neglected as treated above. That is, $D_1 = 0$ has been taken.

Thus we have derived the cosmic evolution of the brane in the presence of energy flow into or from the bulk. By assuming a specific form of the energy transfer which causes the violation of the standard conservation equation of either dark matter or dark energy, we have obtained the modified Friedmann equations (26) and (29). Compared to the usual four-dimensional theory, we have got additional contributions from the bulk-brane energy exchanges which are similar in the third terms of (26) and (29). When $w = 0$, we notice that these two cases coincide with each other. Evolutions of the brane universe described in both (26) and (29) can lead to the late-time acceleration or deceleration depending on the parameters on the model.

We can define the deceleration parameter q by using (26) and (29) and it is easy to see that q can be negative in both cases (see the solid line in Fig. 1). The effective dark energy can be defined as $\rho_{de}^{eff} = \rho_{de1}a^{-3(1+w)} + \rho_{de2}a^n$, where ρ_{de1} and ρ_{de2} correspond to the coefficients of the second and the third terms in (26) and (29), respectively. The equation of state of the effective dark energy can be defined by [30]

$$w_{de}^{eff} = -1 - \frac{1}{3}\frac{d\ln \delta H^2}{d\ln a}, \tag{30}$$

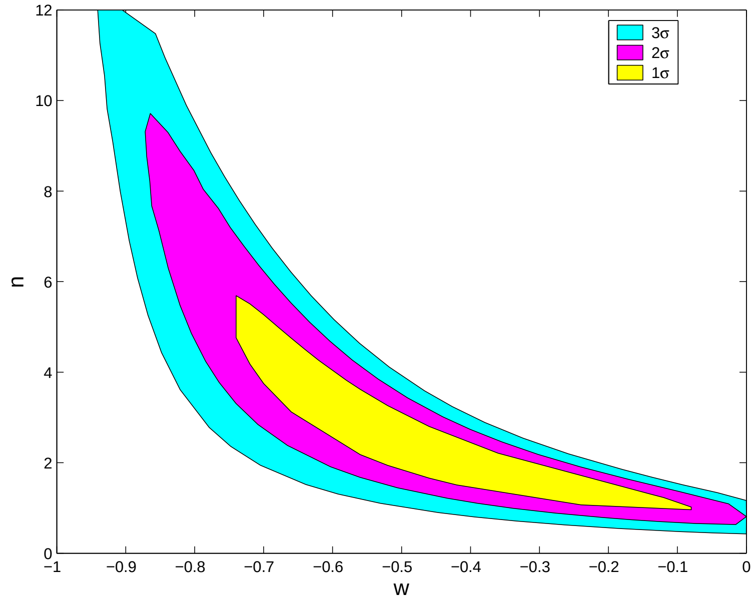

Figure 2: The contour of the parameter space w-n.

where $\delta H^2 = (H^2/H_0^2) - \Omega_m a^{-3}$. It is evolving with time as shown in the dashed line in Fig1. Requiring the deceleration parameter q crossing 0 around 0.5 and the effective equation of state of dark energy w_{de}^{eff} crossing -1 around $z = 0.2$ as indicated by extensive analysis of observational data [20], plus the flatness of the universe, we can reduce the five parameters' space $(\rho_{m0}, C, w, n, T_0)$ in (26) and $(D, \rho_{de0}, w, n, T_0)$ in (29) into two parameters' space (w, n). Fitting the newly released supernova legacy survey data [31], the Sloan Digital Sky Survey (SDSS) data [32] and the Wilkinson Microwave Anisotropy Probe (WMAP) data [33], we obtain that $w = -0.41^{+0.33}_{-0.34}$, $n = 1.99^{+3.70}_{-1.07}$, $\Omega_{m0} = 0.28 \pm 0.02$, $\Omega_{de1} = 0.26^{+0.23}_{-0.15}$, and $\Omega_{de2} = 0.46^{+0.15}_{-0.24}$. We see that in this case, the dark energy with $w = -0.41$ on the brane will no longer violate the causality condition. The contour of $w - n$ is shown in Fig. 2. At the present the equation of state for the effective dark energy is $w_{de0}^{eff} = -1.21$, which is obviously consistent with current observation data [20, 26].

In summary, we have investigated the role of the bulk-brane energy exchange on the evolution of a brane universe. Due to the energy flow between the bulk and the brane, the standard energy conservation is broken. Parameterizing the energy exchange term by the scale factor and Hubble parameter, we have derived the effective cosmological equations in the limit of low energy density on the brane. Compared to the usual Friedmann equation, we have got an additional modified term due to the brane-bulk energy exchange. We found that the modified cosmological picture on the brane accommodates the late time acceleration and the equation of state for the effective dark

energy experiences a transition behavior from above -1 to below -1, while the dark energy on the brane still obeys the causality condition. The "phantom" behavior of the effective dark energy is caused completely by energy flow from the bulk. By fitting the recent type Ia supernova, SDSS and WMAP data, we have shown that the modified gravity on the brane due to the bulk-brane energy exchange is consistent with observations. Further, the effective dark energy equation of state $w_{de0}^{eff} = -1.21$ today shows that our universe is under super-acceleration due to the considered brane-bulk energy exchange. In addition, we note that due to the energy exchange between the brane and the bulk, there will be a big difference between the cases transferring the bulk energy to dark matter and to dark energy on the brane in the effect on the formation of large scale structure. It is of great interest to further investigate this issue.

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